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PROPERTIES OF COMPOUND NUCLEUS FROM EXPERIMENTAL MEASUREMENT OF THE Si^{28} (n, α) Mg^{25} REACTION

by

L. COLLI	(Università di Milano)
I. IORI	(Laboratori C.I.S.E.)
M.G. MARCAZZAN	(Laboratori C.I.S.E.)
M. MILAZZO	(Università di Milano)

1963

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The authors' names are listed in alphabetical order.

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The cross-sections of the Si^{28} (n, α)Mg^{25} reaction for the transition to the ground state and to the first nine excited states of the residual nucleus Mg^{25} have been measured as a function of neutron energy.

The measurement has been made in the neutron energy range 12.15-18.5 MeV, with a beam resolution of about 50 keV from 12.15 to 14.5 MeV, 100 keV from 14.5 to 16.5 MeV, 150 keV from 16.5 to 18.5 MeV. A solid state semiconductor has been used both as a target and as α-particles detector.

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The results of the measurements have been analysed with the theory of the compound nucleus recently developed by Ericson; in particular the amplitude and the width of the fluctuations predicted by this theory have been calculated.

The comparison between the theoretical and experimental values is discussed.

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L. COLLI †, I. IORI, M. G. MARCAZZAN and M. MILAZZO †
Laboratori C.I.S.E., Milano ††

Received 3 December 1962

Abstract: The cross-sections of the $Si^{28}(n, \alpha)Mg^{25}$ reaction for the transition to the ground state and to the first nine excited states of the residual nucleus Mg^{25} have been measured as a function of neutron energy.

The measurement has been made in the neutron energy range 12.15-18.5 MeV, with a beam resolution of about 50 keV from 12.15 to 14.5 MeV, 100 keV from 14.5 to 16.5 MeV, 150 keV from 16.5 to 18.5 MeV. A solid state semiconductor has been used both as a target and as α-particles detector.

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The comparison between the theoretical and experimental values is discussed.

1. Introduction

It has previously [1-3]) been suggested that the validity of the statistical model and the properties of the compound nucleus could be studied through a detailed study of the excitation function of a nuclear reaction.

It was theoretically indicated by Ericson [4]) and experimentally verified [1-3]) that when a reaction takes place with the formation of a compound nucleus, and the excitation conditions of the compound nucleus are such that its levels are completely overlapping, the excitation function presents rapid fluctuations of intensity around its average value. These fluctuations occur when $\Gamma \gg D$, Γ being the width of the excited levels and D their average spacing. The fluctuations come from the interference of the contributions to the reaction of the various levels of the compound nucleus. If the measurement of the excitation function is performed with an energy spread of the incident beam $\Delta E < \Gamma$, it is possible to directly measure the energy correlation of the levels of the compound nucleus, which can be deduced from the width of the fluctuations. The particular interest of this measurement lies in the fact that it is possible to obtain a direct measurement of the half life τ of the compound nucleus, according to the Heisenberg principle $\Gamma\tau \approx \hbar$.

† Also at Istituto di Fisica dell'Università, Milano.
†† This work has been done in cooperation with the nuclear physics group of the Physics Institute of Milan University working under the CNEN-EURATOM program.

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(peaks F and G) a practically continuous contribution of protons from the same reaction is present.

The energy resolution for α particles of our detector is about 1%. The barrier thickness of the detector corresponds to about 4 times the range of the α particles of maximum energy. The correction for the edge effect can be estimated in the most unfavourable case to be of the order of 20%. This value has been evaluated supposing that the α particles are emitted isotropically. No exact calculation can be made, the angular distribution of the α particles themselves being unknown. We have therefore omitted these corrections.

3. Results

For each spectrum obtained, the integrated cross-section for every group of α particles resolved in the spectrum was calculated and plotted as a function of the incident neutron energy. The results are shown in figs. 3-5. They represent in absolute

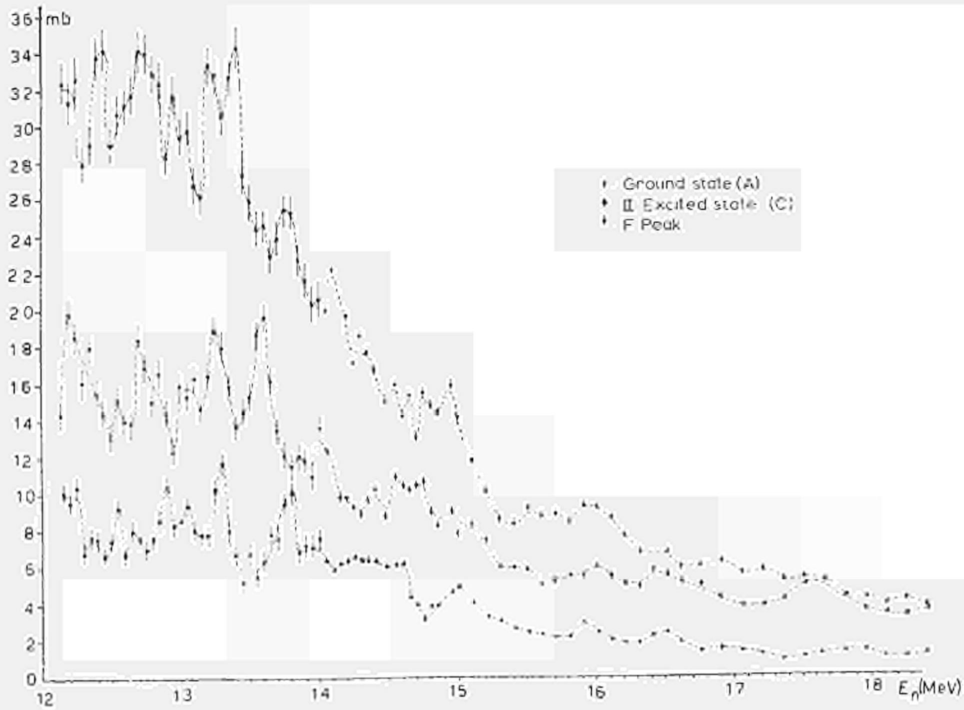

Fig. 3. Cross-sections versus energy of the $Si^{28}(n, \alpha)Mg^{25}$ reaction for the ground state (peak A), the second excited state (peak C) and F peak.

value the integrated cross-section for the individual transitions considered. The absolute values are affected by an error of about 30%. They are in reasonable agreement with some previous determinations [6, 7]).

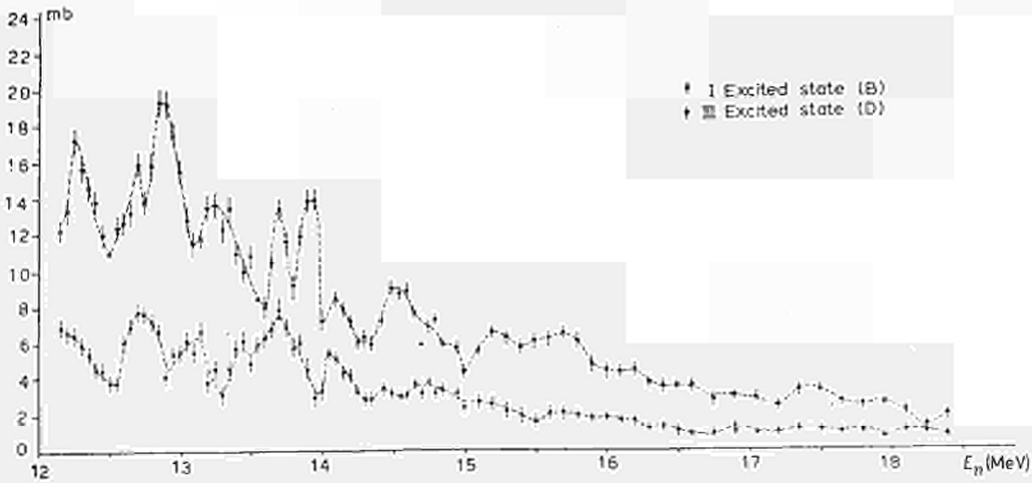

Fig. 4. Cross-sections versus energy of the $Si^{28}(n, \alpha)Mg^{25}$ reaction for the first excited state (peak B) and the third excited state (peak D).

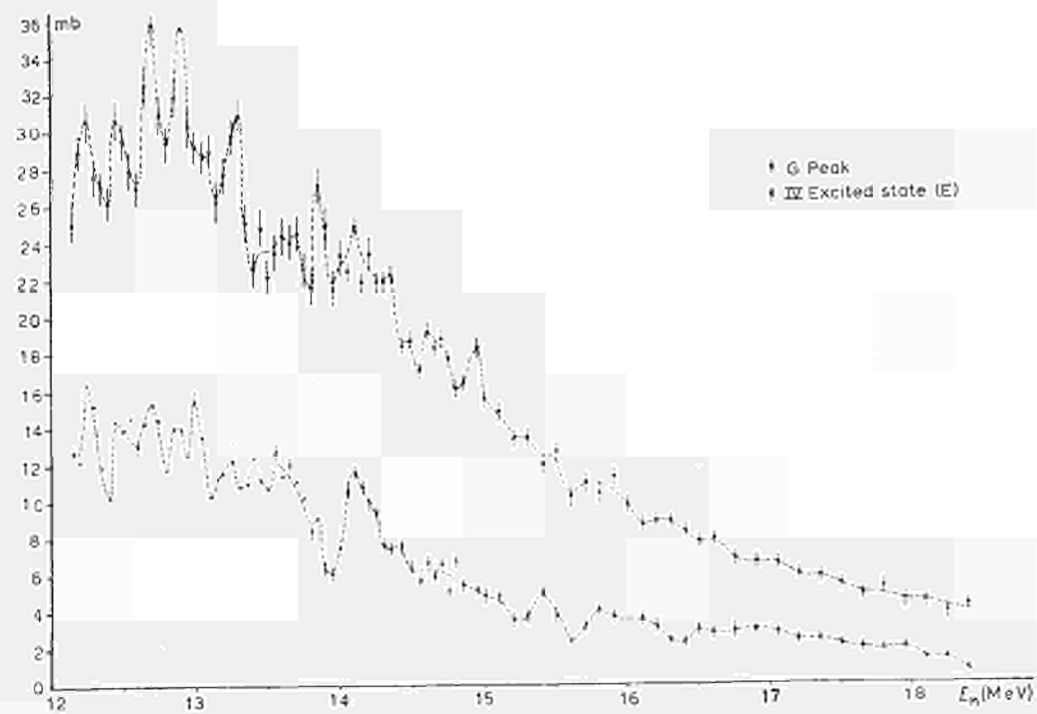

Fig. 5. Cross-sections versus energy of the $Si^{28}(n, \alpha)Mg^{25}$ reaction for peak G and the fourth excited state (peak E).

The average behaviour of these curves supports the hypothesis that the reaction occurs with the formation of a compound nucleus. Above 14 MeV the cross-section decreases with energy in qualitative agreement with the expectations of the statistical evaporation theory; this is due to the opening of an increasing number of outgoing channels. On the basis of the evaporation model, also, it is foreseen that the intensity of the transition on the average and for α-particles above the Coulomb barrier should be proportional to the multiplicity n of final states, that is to the factor $(2j_k+1)$ or $\sum_k(2j_k+1)$ (j_k being the spin of the final state), the latter expression being valid when the peak examined contains transitions to a group of levels not separated.

By integrating the value of the cross-section for each of the peaks measured, over all the energy intervals examined, we obtain values that verify to a first approximation the $2j+1$ dependence. This is shown in fig. 6. The analysis of the fluctua-

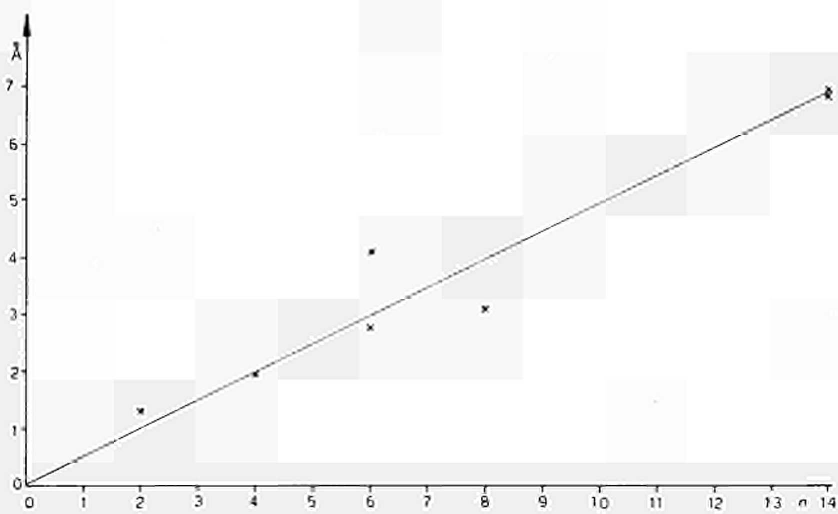

Fig. 6. Averaged cross-sections in arbitrary units for the various peaks versus the multiplicity n.

tions of the excitation functions shows that they have the properties predicted by Ericson; first of all, the different curves do not show correlation between one another as a function of the energy of the incident neutron.

This shows that the position of maxima and minima is not determined only by the excitation energy of the compound nucleus, but depends also on the outgoing channel. In fact it is a phenemenon of interference among the transition amplitudes for the various levels of the compound nucleus which in general are different for different final states. The amplitude of the fluctuations for the integral cross-section can be characterized for each transition by evaluating the mean square deviation.

According to Ericson's calculations [8]), the amplitude of the fluctuations is given by the formula

$$\frac{\langle \Delta\sigma^2 \rangle}{\langle \sigma \rangle^2} = \frac{\sum\limits_{l=0}^{\infty} T_l^{(i)^2}(E_i) \sum\limits_{J=|l-S|}^{l+S} \sum\limits_{I=|J-S'|}^{J+S'} T_I^{(f)^2}(E_f)}{\left(\sum\limits_{l=0}^{\infty} T_l^{(i)}(E_i) \sum\limits_{J=|l-S|}^{l+S} \sum\limits_{I=|J-S'|}^{J+S'} T_I^{(f)}(E_f)\right)^2},$$

where $T_l^{(i)}(E_i)$ are the transparences for neutrons of incident energy E_i and orbital angular momentum l. $T_I^{(f)}(E_f)$ are the transparencies for α particles of energy E_f and orbital angular momentum I, S is the incident channel spin, S' is the final channel spin, and J is the compound nucleus total angular momentum. The calculations were performed by using optical model transparencies [9, 10]) both for neutrons and α-particles.

TABLE 1

Experimental and theoretical values of

$$\sqrt{\frac{\overline{(\sigma-\bar{\sigma})^2}}{\bar{\sigma}^2}}$$

Peak	Excitation energy (MeV)	j	$\sqrt{\frac{\overline{(\sigma-\bar{\sigma})^2}}{\bar{\sigma}^2}}$ Exper.	Theor.
A	0	$\frac{5}{2}$	0.13	0.22
B	0.58	$\frac{1}{2}$	0.24	0.3
C	0.98	$\frac{3}{2}$	0.17	0.26
D	1.61	$\frac{7}{2}$	0.17	0.25
E	1.96	$\frac{5}{2}$	0.15	0.24

The energy interval is 12.15-14.15 MeV.

To evaluate the experimental value of $\langle \Delta\sigma^2 \rangle / \langle \sigma \rangle^2$ we have considered the 12-14 MeV region because here we have the best energy resolution. In table 1 the comparison is shown between experimental and calculated values. The agreement is altogether rather good, if we consider that the finite experimental energy resolution may damp the fluctuations somewhat. The most interesting result of the measurement concerns the energy correlation of the fluctuations. It will be useful to define, in this case, the correlation function as follows [8]):

$$F(\varepsilon) = \langle (\sigma(E+\varepsilon) - \langle \sigma \rangle)(\sigma(E) - \langle \sigma \rangle) \rangle,$$

where ε is a small variable energy interval, and the average must be extended over an energy interval larger than Γ. This product will be different from 0 for $\varepsilon < \Gamma$, because within this interval the values of σ are self-correlated and will tend to 0 for $\varepsilon > \Gamma$, because now the values of σ can be considered random numbers. In the case of the first 5 levels (peaks A-E) where fluctuations are larger the behaviour of this function shows the existence of a correlation interval. To diminish the error due to statistics, we have calculated the average correlation over the first 5 levels of the residual nucleus. This manner of calculation is done under the hypothesis that the correlation interval depends only on the compound nucleus and therefore must be the same for all the curves. The result is shown in fig. 7.

The half width of the curve so defined gives the values Γ, which is the average width of the levels of the compound nucleus. In our case, a value of $\Gamma \approx 90$ keV is found. The half life value that corresponds to 90 keV is about 0.7×10^{-20} sec. This value should now be compared with the theoretical predictions. Using the general statistical formula [4]) and for the parameter a which gives the level density of the final nucleus, the value given by Erba *et al.* [11]), a value of $\tau = 2 \times 10^{-20}$ sec is obtained.

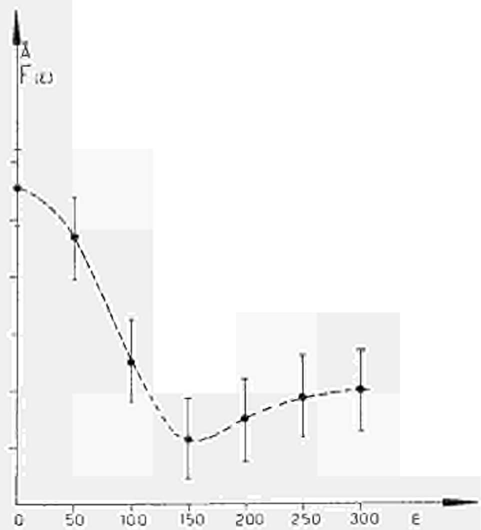

Fig. 7. Averaged correlation function for the A B C D and E peaks in arbitrary units.

It is important to note that the life time[4]) is very sensitive to the values of a chosen for both residual and compound nuclei. A 20% variation of one of them results in a variation by a factor of about 3 in the half life. We note that the parameter a cannot be known better than to within 20%; in fact the values are determined experimentally for contiguous nuclei, and not for those that exactly concern the reaction. Thus, it may be considered that experimental and theoretical values are in agreement, within the errors.

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